Effect of aging on post-saccadic oscillations

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Abstract

Recent research have shown that the eye movement data measured by an eye tracker does not necessarily reflect the exact rotations of the eyeball. For example, post-saccadic eye movements may be more reflecting the relative movements between the pupil and the iris rather than the eyeball oscillations. Since, accurate measurement of eye movements is important in many studies, it is crucial to identify different factors that influence the dynamics of the eye movements measured by an eye tracker. It has been shown that deformation of the internal structure of the iris and size of the pupil directly affect the amplitude of the post-saccadic oscillations that are measured by video-based eye trackers that are pupil-based [1]. In this paper, we look at the effect of aging on post-saccadic oscillations. We recorded eye movements from a group of 43 young and 22 older participants during an abstract and a more natural viewing task. The recording was conducted with a video-based eye tracker using the pupil center and corneal reflection. We anticipated that changes in the muscle strength as an effect of aging [2, 3] might affect, directly or indirectly, the post-saccadic oscillations. Results showed that the size of the post-saccadic oscillations were significantly larger for our older group. The results suggests that aging has to be considered

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as an important factor when studying the post-saccadic eye movements.

Keywords: Post-saccadic oscillation, Iris, Aging, Eye tracking, Eye movements

1. Introduction

When looking at eye movements recorded by an eye tracker, we can see some instability and oscillations that often happen at the end of saccades along the saccade direction before they reach a steady-state value (following fixation). The general term for these instabilities is post-saccadic oscillations(PSO)([4, 1]). Post-saccadic oscillations which may appear both in a form of overdamped or underdamped oscillation were hypothesized to have a neural origin [5], while later studies have shown that the recording technique (dual Purkinje (DPI), scleral search coils, and video-based eye tracking) significantly influences the dynamics of the measured PSOs [6, 7] suggesting that PSOs may have other causes that depend on mechanics of the structures inside the eyeball and the tracking apparatus itself. Slipping of the coil relative to the cornea in coil-based techniques [8] , relative movement between the lens and the cornea in the DPI trackers [6], and deformation of the internal structure of the iris during and directly after saccades in video-based eye trackers that are pupil-based [1], directly affect the amplitude of the measured post-saccadic oscillations. Therefore PSO signals recorded with video-based eye trackers reflect a combination of dynamic overshoot of the eyeball and deformation of the iris (seen as pupil oscillations caused by lens wobble): $PSO = OSC_{eyeball} + OSC_{pupil}$

Nyström et. al. [9] studied the effect of pupil size on pupil center and gaze signals and they showed that the saccade peak velocity and PSO amplitude differ for different pupil sizes. They found it reasonable to think of iris muscles as two springs attached radially to each other where any radial impulse applied to the mass element will make the system oscillate with a higher amplitude when the system is at its natural equilibrium compared to when the equilibrium has already been displaced by a force (constricted or dilated pupil). As the other main factor that influences the oscillations of a spring system is the properties

Figure 1: The experiment recorded participants' eye movements using an Eyelink 1000 eye tracking system.

of the spring itself, it is tempting to study how much PSO signals get affected by changes in elastic properties of the iris. In this paper, we study how post saccadic oscillations change with age. Age is one of the factors that indirectly affects the body tissues and muscles including the muscles of the iris [10]. Studies have shown that the iris gets less reactive [11] and the muscle strength decreases [2] with age.

2. Methods

2.1. Participants and apparatus

The first experiment included 65 participants: 22 older adults (OLD group) with ages ranging from 50 to 80 (mean=69, SD:6.9), and 43 young (YNG group) with ages ranging from 18 to 26 (mean=20, SD:2.6). 16 people from the OLD group and 32 from the YNG group were Male. For the second experiment, we recruited 12 more participants changing the total number of participants as follows: 30 subjects (with ages ranging from 50 to 80 (mean=68.07 SD:7.96), 22 male) in the OLD group and 47 subjects (with ages ranging from 18 to 30 (mean=20.9 SD:2.9), 35 male) in the YNG group. Potential participants were made aware prior to the study that the study involves eye movement measurement. Participants were asked to report 'any related medical history'. One of the participants in the OLD group (involved in both experiments) had cataract surgery and the PSO was almost absent in his data. One participant used glaucoma eye drop and 2 were using dry eyes and hay fever eye drops.

Participants' heads were fixed during the experiments using a chin-rest with a forehead support. The camera was moved horizontally in order to ensure the camera was directly facing the participants' tracked eye. The eye appeared in the center of the eye image for each participant. Eye movement data were recorded from the participants' dominant eye (determined using the Miles test [12] and tracked accordingly) at 500 Hz with the Eyelink 1000 eye tracking system (SR Research Ltd., Ontario, Canada). Participants were sitting 55 cm away from a 24-inch Dell monitor (60 Hz) during the data collection (see Figure 1). The resolution of the monitor was set to 1024 pixels by 768 pixels. Experimenter Builder software Version 1.10.1630 (SR Research Ltd.) was used to control the stimulus events during the eye-tracking task. A single user calibration with 9 points was performed prior to the experiment. The result of the calibration was assessed by doing a validation test using 9 points right after the calibration. The calibration was repeated when the result of the validation reported by the eye tracker was poor.

Older adults were recruited from a local church and younger adults were recruited from a local university. The experiments were conducted at the same lab. Written informed consent was obtained and the study was approved by the National Research Ethics Service (Health Research Authority (HRA), 11/NW/0723).

2.2. Procedure and Data collection

The eye movements were recorded for two different tasks. The first experiment was a pro-saccade task where horizontal eye movements were recorded whilst participants were looking at targets that appear at the left and the right side of the initial fixation point at the center of the screen. In a separate task, participants watched short videos whilst their eye movements were recorded. The second experiment was designed to measure post-saccadic oscillations of more natural eye movements when participants were given different visual search tasks.

3. Experiment 1

Participants completed 16 trials of a prosaccade task. During the task a central fixation target (a white circle with 1° diameter) appeared for 1 second on a black background screen. Following this the saccade target appeared at 4° away from the center for 2 seconds either to the left or right of where the central fixation had been. The saccade target was a red circle with a diameter of 1°. Participants were instructed to look at the central fixation point. Once the saccade target appeared, they were requested to fixate on the target as quickly and as accurately as possible. There was a 200ms blank interval between the fixation target disappearing and the saccade target appearing.

3.1. Data analysis

Fixation and saccade detection was done by the EyeLink software (DataViewer) using the default 'cognitive configuration' parameters. Therefore saccade velocity threshold was $30°/sec$, saccade acceleration threshold was $8000°/sec^2$. The peak velocity of the saccades used in the paper was determined as the maximum of the reported velocity during the saccade.

Since in the first experiment targets were shown at fixed positions either at the left or at the right side of the resting fixation (defined at the middle of the screen), only horizontal components of the eye movement data were considered.

We then extracted all the saccades that had a starting point within 2 degrees of the middle of the screen with a latency between 100-1000 ms and an amplitude within 75-125% of the target amplitude (distance of the target from the resting fixation in the screen). All the gaze data that belonged to the saccades that were towards the right target were rotated by 180 degrees (in the screen coordinate system) such that we can study all the left and right saccades together. Hooge et al. (2015) [13] have observed that the shape of the PSO signals may be very different for abduction and adduction saccades and for left and right eyes. However, in our first experiment the initial fixation is always at the center of the screen and during the experiment only one of the eyes are tracked. Furthermore, the saccade amplitude was similar (about 4°) for all the saccades. Therefore, all the recorded saccades (either towards the left or towards the right) were abduction saccades and the overall shape of the PSO signals for the leftward and rightward saccades were quite similar for each participant. From now, for the sake of brevity we refer to the horizontal components of the selected saccades as PSO signals that change over time.

3.1.1. Signal alignment

We skipped the first 20% of the total samples recorded for each saccade and also included 20 frames (40 ms) of eye data after the end of each saccade to ensure that the most oscillating part of the signals are included. All the PSO signals were spatially aligned based on the fixation location at the end of each saccade (defined by the median of the eye data within the range of 20-30 ms after each saccade). Each signal was shifted along the spatial axis such that all the signals converge at zero (see Figure 2). We then found the minimum peak of each oscillation by searching for the first critical point of the signal curve that happens after the maximum velocity. Finally, the signals were aligned temporally by aligning their minimum peak on a new common timeline. Because different saccades may have different amplitude, we define the reference point (zero) along the time axis at the point at which all minimum peaks are aligned in time. Figure 2 shows an example of PSO signals aligned for one of the OLD subjects (chosen randomly).

3.1.2. PSO median and amplitude and variation

We calculated the median of all PSO signals for each individual participant which summarizes all the PSO signals into one signal. Figure 2 also shows the median PSO (red curve) for a randomly chosen participant. We used median instead of mean to reduce the effect of any outlier such as: signals that are not aligned properly, noisy signals, missing samples and also signals with different shapes.

The amplitude of each individual PSO signal (and the median PSO) was defined as the distance between the first occurrence of the minimum and the first occurrence of the maximum value of the signal within the interval of 0-40ms (see Figure 2). We used this method (as used by [1]) instead of the method used by [13] because it was easier and more reliable to automatically run on a large number of PSO samples obtained in our study with different shapes of waveform (waveforms with one, two or three bumps). The amplitude obtained from this method may not represent the actual amplitude of the PSO when a drift component is present in the PSO signal ([13]), however, it provides a good representation of the amplitude of the oscillation component of the PSO waveform regardless of the drift.

We also use the standard deviation of the value of all PSO signals at time 0 to indicate the level of inconsistency of the PSO signals for each participant and we refer to it as PSO variation (see Figure 2).

3.2. Results

Data quality across the two groups was primarily checked by looking at the gaze tracking accuracy obtained from the validation step (which was done after each calibration). The mean of the average error was 0.35 (SD=0.16) degrees of visual angle for the YNG group and 0.45 (SD=0.32) degrees for the OLD group. The mean of the maximum error was 0.63 (SD=0.29) degrees for the YNG group and 0.98 (SD=0.26) degrees for the OLD group.

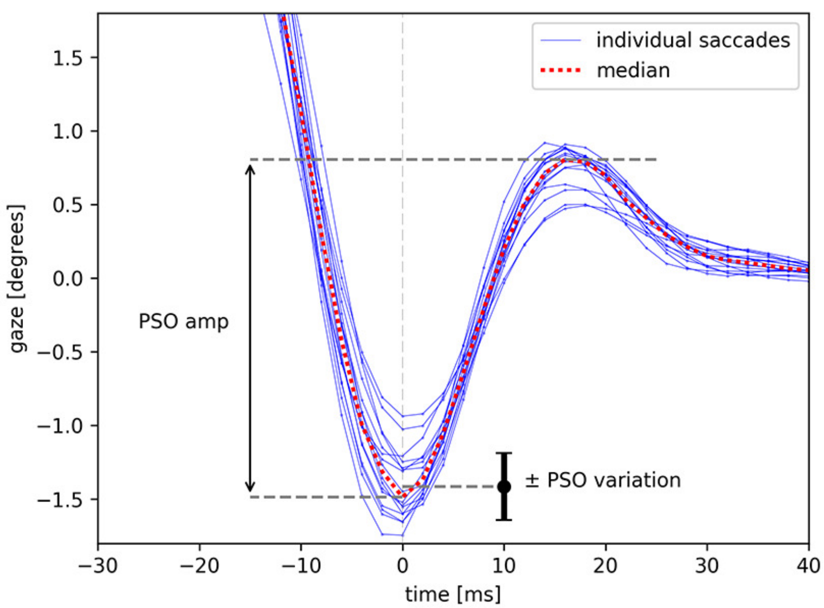


Figure 2: 16 PSO signals collected form the first experiment for a randomly chosen subject (from the OLD group). The red curve shows the median PSO.

The mean saccade latency measure from the onset of the targets was 211.4 ms(SD=63.06) for the OLD group and 184.8 ms (SD=52.50) for the YNG group. The average saccade peak velocity was 231.73 deg/s(SD=53.22) for the OLD group and 214.52 deg/s (SD=48.34) for the YNG group. The average saccade amplitude was 3.95 deg (SD=0.57) for the OLD group and 4.2 deg (SD=0.85) for the YNG group.

Based on the search criteria defined in section 3.1, in average, 14.93 (SD= 1.82) saccades per subject in the YNG group and 14.63 (SD= 2.31) saccades per subject for the OLD group was detected. To be able to compare the PSO signals of the two groups, participants were represented by their median PSO signals. Figure 3 shows the median signals of the old (OLD) and the young (YNG) groups. The figure shows that in the OLD group, the amplitude of the oscillations tend to be larger than in the YNG group. A t-test was conducted to see whether the difference between the signal amplitude are significant. The result ($t_{(61)} = -5.33, p < .05$) indicates that the mean of PSO amplitude of the OLD group ($M = 0.95, SD = 0.53$) was significantly higher than the mean of the YNG group ($M = 0.41, SD = 0.26$). However, no significant difference was found between the PSO variations of the two groups and the mean PSO variations in both groups were between 0.1-0.2°.

4. Experiment 2

In the second experiment, participants' eye movements were recorded whilst they were watching three short videos on three occasions (a free view session and two instructed sessions). The video clips were taken from (1) Coronation of the Queen Elizabeth II, (2) Gordon Brown and family leaving Downing Street after losing the general election in 2010, and (3) Neil Armstrong landing on the moon. Prior to the viewing of each video the participant was given instructions related to the video. In the free view session participants were asked to freely watch the video. In the second two instructed sessions a specific question was asked about the video which was designed to direct the top-down control of eye gaze (e.g.

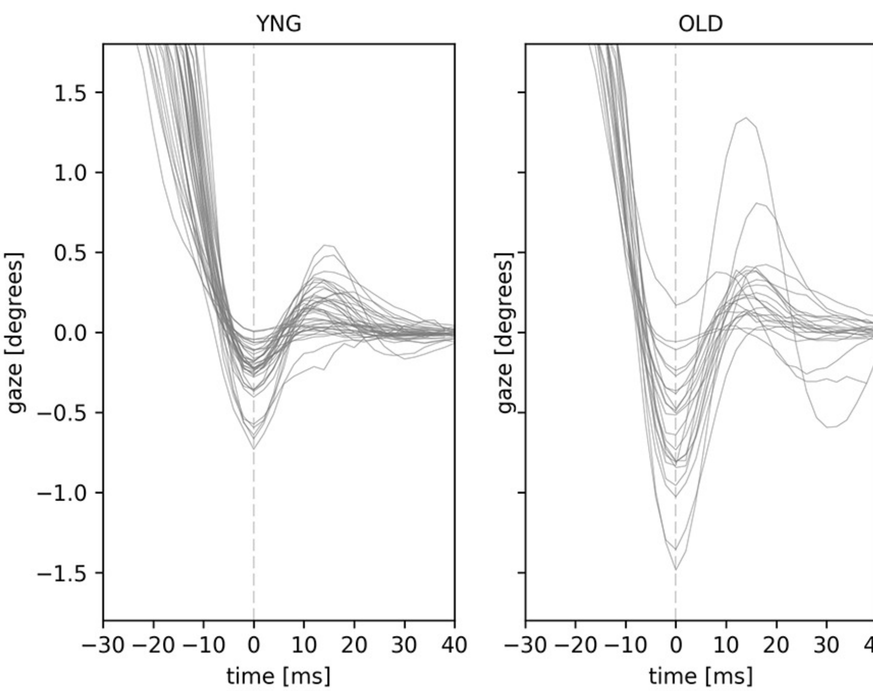


Figure 3: Median PSO signals of all the participants in the young group (left plot including 41 signals) and the old group (right plot including 22 signals) collected from the first experiment.

How many windows are there on the buildings?, or How many bald men are in the room?). In total, we collected data from 9 video trials per participant. Each video lasted 40 seconds. The main goal of the second experiment was to record as many saccades as possible from a natural task of watching a video in different viewing conditions rather than whether the participant answered the question correctly.

4.1. Data analysis

In total 14557 PSOs signals were obtained from the OLD group with the average of 766.1 per participant (SD=196.1), and 30262 from the YNG group with the average of 703.8 per participant (SD=167.5). Saccade detection was done in the Eyelink tracking software with the velocity and acceleration thresholds of $30°/s$ and $8000°/s2$, respectively; The data from 1 of the OLD participants was excluded from the analysis of the second experiment due to poor overall quality and eye-tracking instability. Unlike experiment 1 where saccades were mainly horizontal and all were within a specific range of amplitude, in this experiment the collected saccades were in different directions and different amplitudes. After extracting each saccade from the eye movement data, we rotated the gaze data of the saccade by the angle between the saccadic eye movement and the horizontal axis. The slope of the line connecting the coordinates of the start point of the saccade to the fixation coordinates at the end of the saccade (defined by the median of the eye data within the range of 20-30 ms after each saccade) was taken as the slope of the saccade. The PSO signal of each saccade is then defined by the horizontal component of the gaze data over time. This made it possible to include and compare all saccades in the analysis. However, summarizing over 700 signals per participant into one signal using either mean or median could be problematic if the shape of the signals are very different from each other. In our experiment, majority of the signals obtained from each participant had the standard shape of an under-damped harmonic oscillation with an downward bump followed by a upward pump (similar to Figure 4) which was consistent for each participant regardless of the saccade direction and the

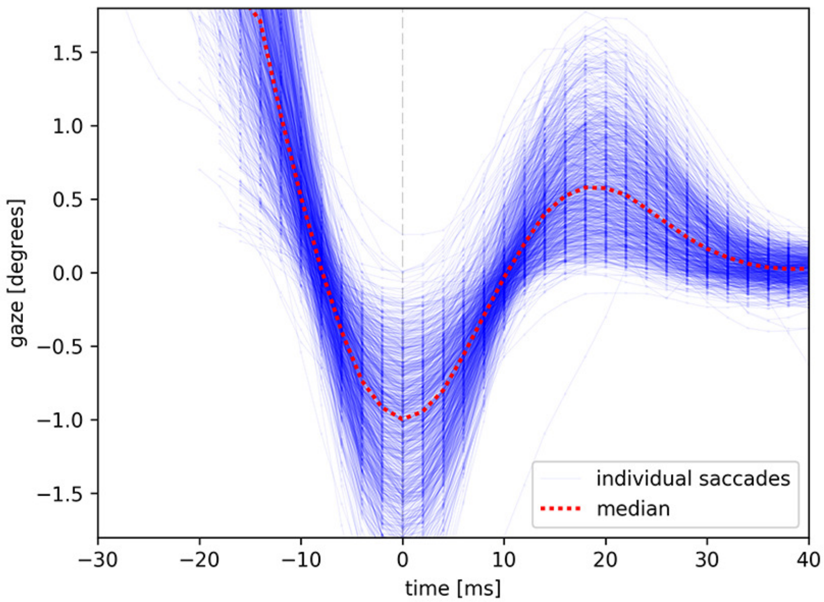
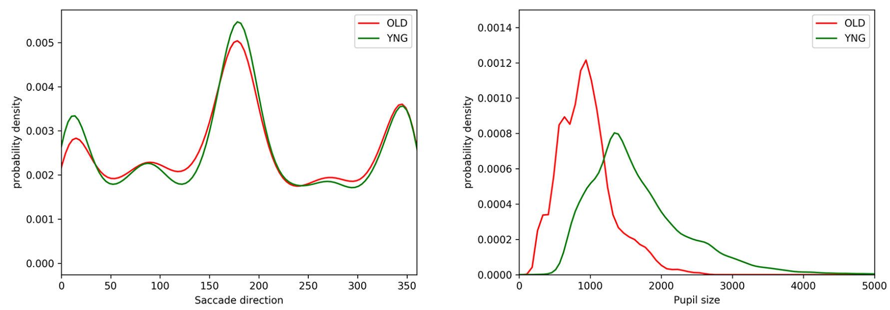


Figure 4: 799 PSO signals for a randomly chosen participant (from the OLD group) collected from the second experiment.

amplitude. However, the amplitude of the PSO signals could vary significantly depending on the amplitude of the saccade.

Figure 4 shows an example of 779 PSO signals for the same subject as shown in Figure 4 that was randomly chosen from the OLD group (this includes all saccades in different directions obtained from 9 video trials). We used the same alignment approach that we used in Experiment 1 for aligning the PSO signals in this experiment.

Figure 5a shows the distribution of the saccade direction for all the saccades obtained from the OLD and YNG groups using kernel density estimates. The figure reveals that the horizontal saccades were the most frequent saccade direction in both groups as was expected according to the previous studies [14].



(a) (b)

Figure 5: Kernel density plots showing the distribution of saccade direction (a) and pupil size (b). The red curves belong to the OLD group and the green curves are for the YNG group.

4.2. Results

Based on the result of the validation test (performed after each calibration), the mean of the average gaze tracking error was 0.4 (SD=0.21) degrees of visual angle for the YNG group and 0.47 deg (SD=0.46) for the OLD group. The mean of the maximum error was 0.64 deg (SD=0.45) for the YNG group and 0.83 deg (SD=0.58) for the OLD group. The mean of the fixation count in the YNG group was 939.49 (SD=202.41) and was 1030.73 (SD=197.19) in the OLD group. The mean of the fixation duration in the YNG group was 384.59 ms (SD=72.56) and was 325.32 ms (SD=56.72) in the OLD group.

As peak velocity and the pupil size (at the end of each saccade) were different for the saccades recorded in the video watching experiment, we looked at the distribution of peak velocities and pupil sizes as well as the PSO amplitude. Thus, we first compared the saccades of both groups based on their amplitudes and peak velocities.

4.2.1. Saccade peak velocity and amplitude

Figure 6 shows the relationship between the peak velocity and amplitude (i.e. Main Sequence [15]) of all the collected saccades where each point represents a saccade. Each curve in the figure represents the main sequence for each

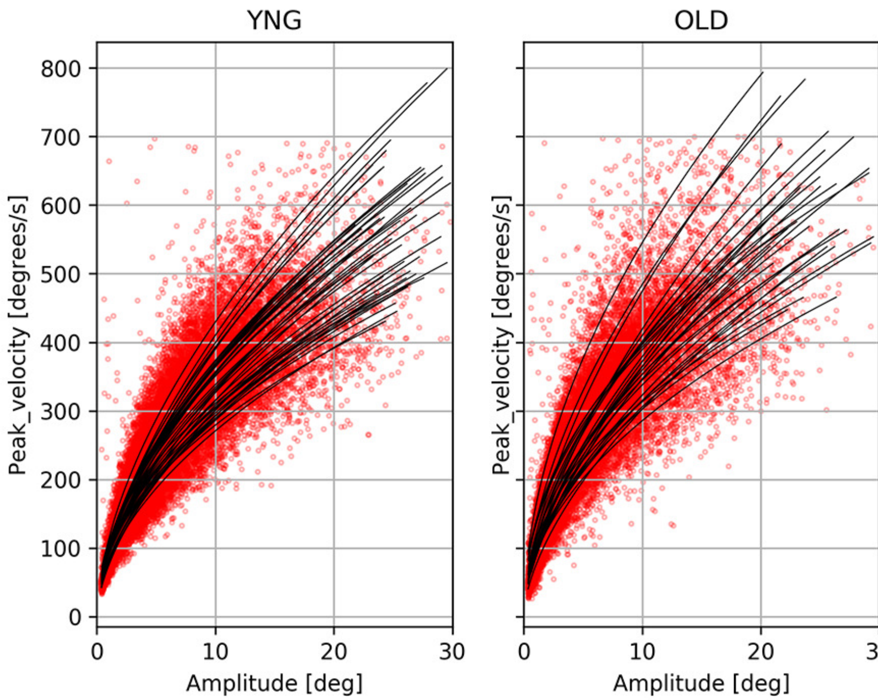


Figure 6: Amplitude and peak velocity of all collected saccades. Each curve shows the power function fitted to the saccades of an individual subject.

participant with a power law function ($v_{peak} = K amplitude^L$) [16] fitted to all the sample points that belong to that participant with 95% confidence interval.

The average saccade amplitude was 5.12 deg (SD=0.73) for the OLD group and 5.28 deg (SD=0.67) for the YNG group.

4.2.2. Pupil diameter

Although the brightness of the screen and the light condition was similar for all participants, the pupil size still slightly vary between subjects due to the individual differences of the optics of the eyes, optical distortion of the cornea of the eye, and also because of the eye movements that change the appearance of the pupil in the eye image [1]. Age difference between our two groups was another factor which caused differences in pupil size [10, 17].

In our experiment, pupil diameter was measured as the pupil area in system units. Figure 5b shows the histogram of the pupil size for all collected saccades for both participant groups. From the histogram we can see that the pupil size was relatively smaller for the OLD group compared to the YNG group.

4.2.3. PSO variation

Similar to the first experiment, we found no significant difference between the PSO variations of the two groups and the mean PSO variations in both groups were between 0.5-1.0°.

4.2.4. PSO amplitude

Figure 7 shows the median PSO signal for each participant within the YNG and the OLD group. PSO signals are colored differently for different peak velocities. To be able to compare the PSO signals of the two groups independent of the effect of peak velocity, we calculated the PSO amplitude (difference between the minimum and the maximum peak of the oscillation) for all signals for different ranges of peak velocities (Figure 8). A one-way ANOVA was conducted on the PSO amplitude between the OLD and the YNG groups and the result showed a significant difference between the PSO signals of the two groups at the $p < .05$ level across all ranges of peak velocities $[F(1, 60) = 49.72, p = 0.000]$. Post hoc comparisons using Holm-Bonferroni Sequential Correction test indicated that across all ranges of the peak velocity the mean of PSO amplitude for the OLD group was significantly higher than the mean amplitude of the YNG group at $p < .05$.

Figure 8 shows that overall, the size of the PSO increases or the level remains unchanged (in the OLD group) as the saccade peak velocity increases. Figure 9b, on the other side, shows the PSO amplitude versus saccade peak velocity

[1] According to the EyeLink manual, pupil size measurements are affected up to 10% by pupil position

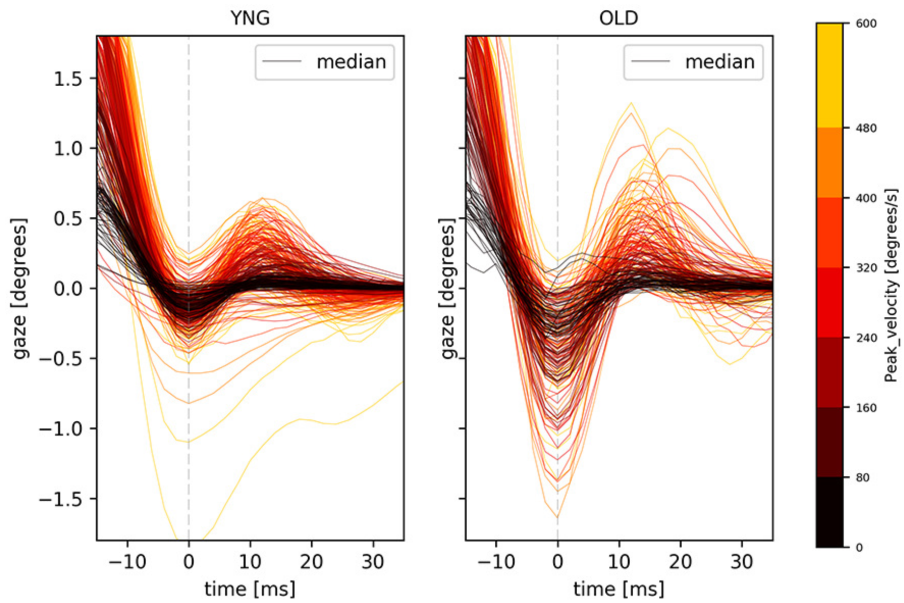


Figure 7: PSO signals of all the saccades for OLD and YNG groups. Each signal shows the median of all recorded signals per subject. Colors represent the peak velocity for each PSO.

and changes in the PSO amplitude of each individual is shown by fitting a second-order polynomial to their data. Overall (except for a few subjects), the PSO amplitude grows as the peak velocity increases. This is not surprising as previous studies have also shown that amplitude and peak velocity of the saccade significantly affect the PSO amplitude ([18, 13]). However, it is shown that for saccade size larger than 8° PSO amplitude decreases with increasing saccade size [13]. To see this in our data, we plotted the PSO amplitude versus saccade amplitude Figure 9a. We also observed a decrease in the PSO size for saccades larger than about 8° and this decrease was even more apparent in the OLD group.

4.3. Linear regression Analysis

Pupil size is another factor that has influence on the PSO signals [13, 9]. In order to make sure that any significant difference that we find between the PSO amplitude of the two groups is specifically related to age and not other factors

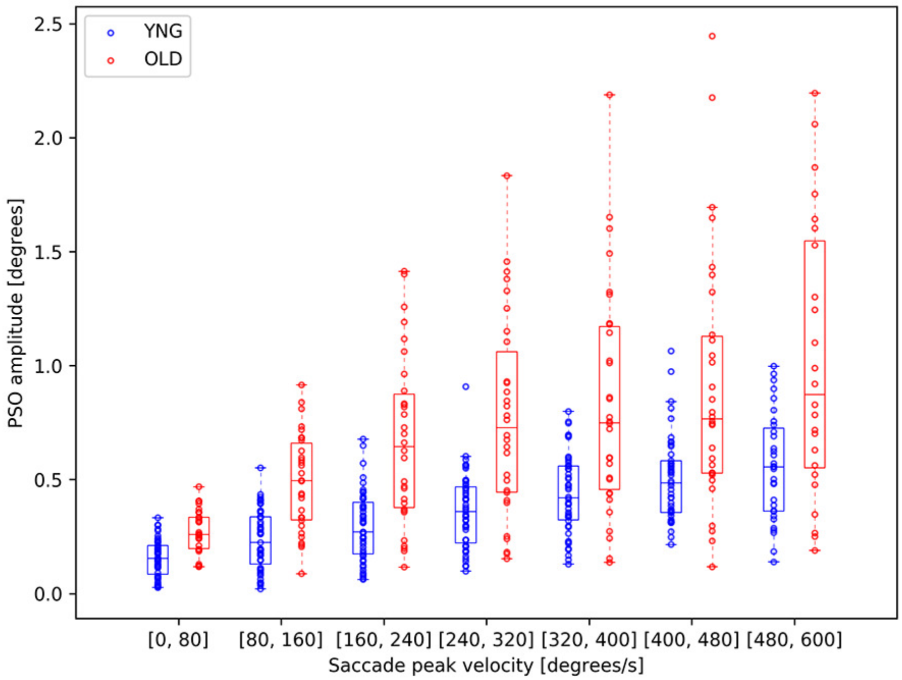
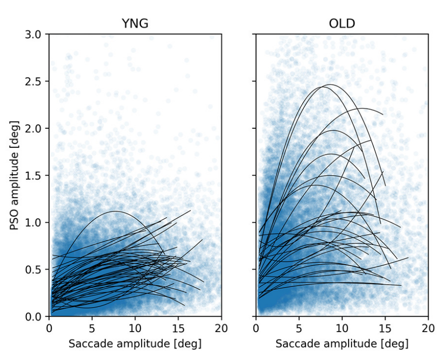
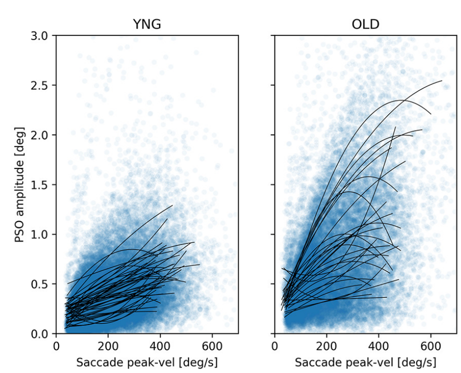


Figure 8: PSO amplitude of OLD and YNG groups for different ranges of saccade peak velocity. Each circle represents the amplitude of the median PSO (only for signals within the range of the peak velocity) for each participant. Number of samples are shown above each boxplot.



(a)



(b)

Figure 9: PSO amplitude vs saccade saccade amplitude (a), and PSO amplitude vs saccade peak velocity of both groups (b). Each curve represents an individual subject.

such as pupil size, we conducted a multi-variable linear regression analysis. To keep the model simple, we first performed the linear regression ([19]) describing the median of all available variables obtained per subject (median of PSO amplitude (PSO_{amp}) as a linear function of age (YNG vs OLD, I_{OLD} is an indicator of being in the OLD group), saccade peak velocity (V_{peak}), and pupil size (P)). Since the raw data violates the linear regression assumptions (constant variance and normality of residuals) we transform the PSO_{amp}, V_{peak} and P variables. We considered various transformations and the log transformation was the most appropriate for all variables except age. The most (statistically) appropriate model for the data is Eq. 4.3 where log(PSO amplitude) is a function of log(saccade peak velocity) and age (R^2:0.501). Interestingly pupil size did not have a significant effect (t-test, p=0.0901, 95% confidence (-0.043, 0.584)) on median PSO amplitude once saccade peak velocity and age had been taken into account.

$$\log(PSO_{amp}) = \beta_1 + \beta_2 \log(V_{peak}) + \beta_3 I_{OLD} \log(V_{peak}) \qquad (1)$$

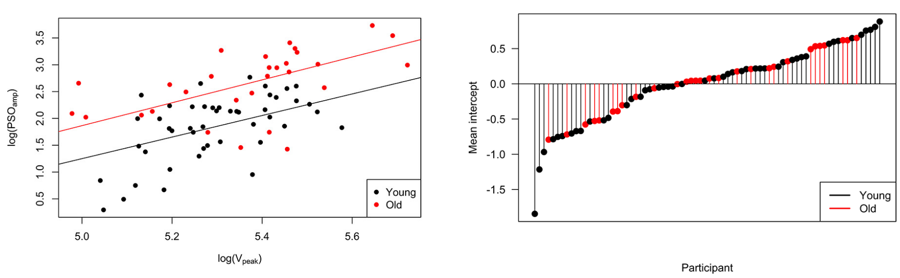
The values of the fitted model are described in Table 1 and Fig. 10a. The result shows a significant relationship between the PSO amplitude and the term $\log(V_{peak})$ indicating that as log(peak velocity) increases, log(PSO) increases slightly more for the OLD than for the YNG group. This demonstrates that the median PSO amplitude for a typical person in the older group is their peak velocity to the power 0.123 times that of a typical person in the younger group. For our participants this was between 1.845 and 2.022 times that of the younger group.

4.4. Linear mixed-model analysis

The linear regression analysis from Section 4.3 was adequate but it collapsed all the saccades from a person into a single median value for PSO amplitude. Ideally we would like to model at the individual saccade. However, under the traditional linear regression framework we cannot do this as several observations belong to the same person and hence might be correlated - this violates

Table 1: Results of the linear regression analysis. Each of the variables in our final model alongside its estimate, 95% confidence interval and p-value.

	Estimate	CI		p-value
		2.5%	97.5%	
$\log(V_{peak})$	2.010	1.238	2.782	1.88×10^{-06}
$I_{OLD} \log(V_{peak})$	0.123	0.076	0.170	1.60×10^{-06}



(a) (b)

Figure 10: (a) Linear Regression model fit from Table 1. (b) Mean random effect intercepts per participant accompanying the estimates of the fixed effects from Table 1.

the assumption of uncorrelated errors. An extension to linear regression that allows for correlated errors by group is called Linear Mixed Models (LMMs) ([20]). In LMMs we model the PSO amplitude of each individual saccade as a linear combination of age, saccade peak velocity and pupil size (or appropriate transformations thereof) as before. The difference comes in the addition of a "random effect" term which allows each person to have their own separate intercept. In effect we give each person their own regression line; every person has the same parameters for age, saccade peak velocity and pupil size but each person has a different "height" on the y-axis (see Fig. 10b).

The most (statistically) appropriate mixed model ([21]) is given in Eq. 2 where log(saccade PSO amplitude) for person j is a function of log(saccade peak velocity) and age as previously but also a function of the square root of pupil size (R^2:0.613, [22]). The u_j term is the additional term allowing a different intercept for each person.

$$\log\left(PSO^{j}_{amp}\right) = \beta_{1,1}\beta_2\sqrt{P} + \beta_3 \log\left(V_{peak}\right) + \beta_4 I_{OLD} \text{ where } \beta_{1,j} = \beta_1 + u_j. \quad (2)$$

The values of the fitted mixed effects model are given in Table 2 and Fig. 10b. This demonstrates that the PSO amplitude for a typical person in the older group is 2.809 times that of a typical person in the younger group. Compared to the linear regression analysis, the result of the LMMs analysis shows that the effect of both pupil size and age on the PSO amplitude are significant.

For data this large (62,313 saccades) a p-value test is not appropriate as for datasets of this size almost any effect is significant. To gauge an idea as to whether the variables were significant only due to the sample size we randomly sampled the data in sizes from 100 to 60,000 each time fitting Eq. 2 and considering the confidence interval for each variable. Plots of this experiment are given in supplementary material and demonstrated that the effects seen here are not due to the the large sample size.

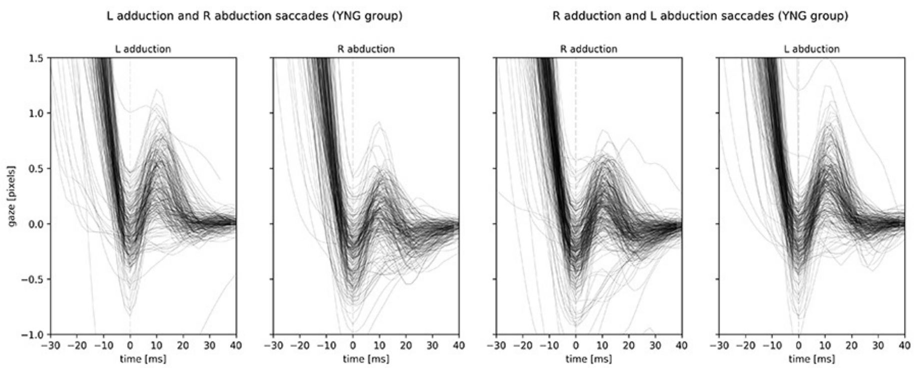
Table 2: Results of the linear mixed model analysis. Each of the variables in our final model alongside its estimate, 95% confidence interval.

	Estimate	CI	
		2.5%	97.5%
$\sqrt{P}$	0.027	0.026	0.029
$\log(V_{peak})$	0.524	0.516	0.532
I_{OLD}	1.033	0.788	1.277
σ_u	0.527	0.447	0.615

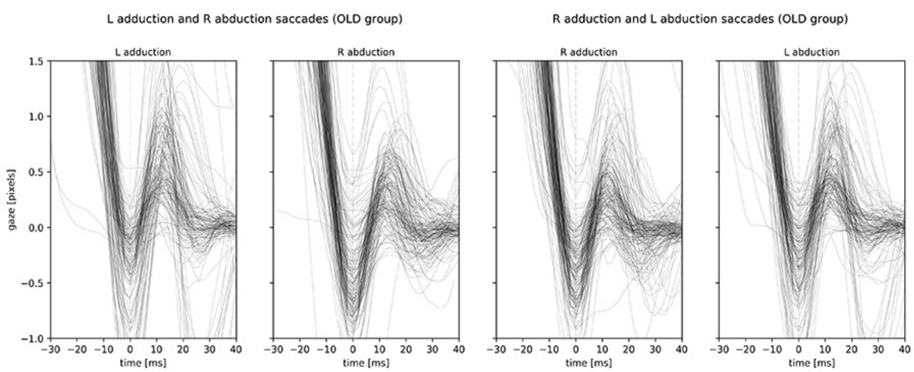
5. Discussion

In this study, we observed that the post-saccadic oscillations significantly vary between two age groups. The PSO amplitude recorded by a video-based eye tracker was larger for older participants regardless of the effect of saccade peak velocity and the pupil size. Our finding is different than what has been found by Deubel and Bridgeman (1995) [23] on data recorded by dual Purkinje eye trackers (DPIs). Deubel and Bridgeman (1995) showed that post-saccadic overshoots (and backshoots) decrease in magnitude with age. However, in their study, there were only two subjects older than 50 years while our observations are based on more subjects. These different findings may also be due to different eye trackers used in the two studies. The PSO signals recorded by a DPI eye tracker is related to the motion of the lens, whereas the PSO signals recorded by a video-based eye tracker is related to the motion of the pupil center inside the eyeball. Deubel and Bridgeman (1995) explained that the smaller PSOs in the older subjects may be due to the reduced flexibility of the lens and reduction in the elasticity of the ocular tissues. By the same reasoning, we expect that even the pupil should appear less wobbly with age. However, it is less obvious how aging affects the overall elasticity of the iris as a system that contains two sets of muscles (radial and circular muscles). Surprisingly, our result showed that the PSOs were even larger for the older subjects compared to the younger group. It should be noted that the PSO signals used in this paper were extracted from the gaze data recorded by a P-CR eye tracker. The gaze-PSOs are not exactly representing the oscillations of the pupil and they are usually larger than CR-PSOs (oscillations of the corneal reflection signal) and pupil-PSOs ([24]). Therefore, it is unclear whether the increase in the PSO amplitude in older subjects is because of larger pupil oscillations at the end of each saccade or because of the larger oscillations of the corneal reflection which is caused by the oscillations of the eyeball and the corneal bulge. After aligning and plotting nearly 700 PSO signals for each of our 76 subjects, we found that PSOs are very reproducible within participants and they are similar in shape (frequency and the number of peaks) whereas the amplitude of the signals vary for different saccade peak-velocities. As mentioned earlier, previous studies [13] have shown that the shape of the PSO signals may look very different for abduction and adduction saccades specially for saccades larger than 10°. We specifically looked at different subsets of saccades: those that started from the central region of the screen (±2° from the center) and moved towards the left or the right side of the screen (leftward and rightward abduction saccades), and also those that started from the left and the right sides and moved towards the center (leftward and rightward adduction saccades). For this, we only included the horizontal saccades with the slope angle of ±2° and those that had large amplitudes between 8° to 30° (maximum amplitude). Figure 11 shows all individual PSO signals that meet these criteria. In average, each plot in the figure includes 3-5 signals per participant which is a small percent of the total signals. The figure reveals that the shape of majority of the PSO signals recorded in the second experiment does not differ even for large size saccades and between adduction and abduction saccades.

Based on our result, we argue that age has to be considered as an effective factor when employing video-based eye trackers (that use pupil center) for measuring the true trajectory of persons' saccadic eye movements and for analyzing saccade dynamics. Future work with data collected from more subjects at different ages will investigate whether there is a linear or non-linear correlation between PSO amplitude and age (as a continuous variable).



(a)



(b)

Figure 11: Leftward/rightward adduction and abduction saccades for YNG (a) and OLD (b) groups.

The increase in the scale of PSO in older populations is likely to have an impact on visual perception in relation to the timescale of the saccadic eye movement. Traditionally, saccades have been associated with a period of visual suppression that is linked to the duration of the saccadic eye movement [25, 26]. However in their elegant study, Burr, Morrone & Ross (1994) demonstrated that saccadic suppression was selective across the spatial frequency domain [27]. During saccades it was more difficult to detect the low spatial frequencies, the detection of high spatial frequencies was facilitated. It is therefore conceivable that PSOs contribute to this effect on the visual sensitivity of spatial frequency, by enhancing the detection of high spatial frequencies towards the end of the saccade. Our results suggest that for older people this phenomenon may be exaggerated, possibly as a result of a natural adaptive and compensatory mechanism to mitigate against the loss of visual acuity (i.e. high spatial frequency vision) in old age).

The results of this study have implications for researches that study saccadic and post-saccadic eye movements. Also the result of our study can be of interest to works that have looked at the use of PSOs as a biometric for human identification [28].

6. Acknowledgments

The work described in this paper is funded by EPSRC project EP/M006255/1 Monitoring Of Dementia using Eye Movements (MODEM).

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